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### **Baryon spectroscopy in constituent quark models.**

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### **Abstract**

We present a study of the baryon spectra for all flavor sectors within a constituent quark model. We address some of the outstanding problems in baryon spectroscopy, as for example the spin splitting evolution for the different flavor sectors, the flavor independence of confinement and the missing state problem.

### **1 The light sector**

The complexity of Quantum Chromodynamics (QCD), the quantum field theory of the strong interaction, has prevented so far a rigorous deduction of its predictions even for the simplest hadronic systems. In the meantime while lattice QCD starts providing reliable results, QCD-inspired models are useful tools to get some insight into many of the phenomena of the hadronic world. One

of the central issues to be addressed is a quantitative description of the low-energy phenomena, from the baryon-baryon interaction to the baryon spectra, still one of the major challenges in hadronic physics.

Nowadays, we have at our disposal realistic quark models accounting for most part of the one- and two-body low-energy hadron phenomenology. Among the quark models found in the literature <sup>1)</sup>, the ambitious project of a simultaneous description of the baryon-baryon interaction and the hadron spectra in all the flavor sectors has only been undertaken by the constituent quark model of Ref. <sup>2)</sup>. The success in describing the properties of the strange and non-strange one and two-hadron systems encourages its use as a guideline in order to assign parity and spin quantum numbers to already determined baryon states as well as to predict still non-observed resonances.

The results we are going to present have been obtained by solving exactly the Schrödinger equation by the Faddeev method in momentum space. The results are of similar quality to others present in the literature based on models specifically designed for the study of the baryon spectra <sup>3)</sup>. In the constituent quark model used in this work the hyperfine splitting is shared between pseudoscalar forces and perturbative QCD contributions, provided by the one-gluon exchange. In Table 1 we give the contribution of different pieces of the interacting hamiltonian to the energy of several octet and decuplet baryons. One observes that the hyperfine splittings are controlled by the one-gluon exchange (OGE) and one-pion exchange (OPE) [one-kaon exchange (OKE)] potentials in the non-strange [strange] sector. The OGE and OPE generate almost the experimental hyperfine splitting, the one-eta (OEE) and one-sigma exchange (OSE) given a final small tune. The expectation value of the OPE flavor operator for two light quarks is replaced by the similar effect of the OKE when a light and a strange quarks are involved. They enhance in a similar way the hyperfine splitting produced by the OGE. The important effect of the OGE is observed when Table 1 is compared to Table II of Ref. <sup>4)</sup>. The contribution of the pseudoscalar forces is much smaller in our case, generating decuplet-octet mass differences of the order of 100–200 MeV, the remaining mass difference given by the OGE.

Table 1: Eigenvalue, in MeV, of the kinetic energy combined with different contributions of the interacting potential. The subindexes in the potential stand for: 1 = *CON*, 2 = 1+*OGE*, 3 = 1+*OPE*, 4 = 2+*OPE*, 5 = 3+*OKE*, 6 = 5 + *OEE*, 7 = 6 + *OSE*. Experimental date is taken from the PDG.

State	$V_1$	$V_2$	$V_3$	$V_4$	$V_5$	$V_6$	$V_7$	Exp.
$N(1/2^+)$	1534	1254	1407	969	969	1030	939	939
$\Delta(3/2^+)$	1534	1314	1510	1291	1291	1283	1232	1232
$N^*(1/2^+)$	1787	1601	1716	1448	1448	1479	1435	1420–1470
$N(1/2^-)$	1722	1530	1675	1422	1422	1447	1411	1515–1525
$\Sigma(1/2^+)$	1679	1417	1674	1408	1326	1229	1213	$1192.642 \pm 0.024$
$\Sigma(3/2^+)$	1679	1462	1673	1454	1437	1438	1382	$1383.7 \pm 1.0$
$\Sigma^*(1/2^+)$	1983	1757	1931	1752	1703	1688	1644	1630–1690
$\Sigma(1/2^-)$	1859	1677	1854	1671	1645	1634	1598	$\approx 1620$
$\Lambda(1/2^+)$	1679	1405	1600	1225	1171	1217	1122	$1115.683 \pm 0.006$
$\Xi(1/2^+)$	1819	1557	1819	1557	1472	1446	1351	$1321.31 \pm 0.13$
$\Omega(3/2^+)$	1955	1743	1955	1743	1743	1728	1650	$1672.45 \pm 0.29$

## 2 The missing state problem

Constituent quark models of baryon structure are based on the assumption of effective quark degrees of freedom so that a baryon is a three-quark color-singlet state. Lattice QCD in the quenched approximation shows out a  $qq$  confining potential linearly rising with the interquark distance<sup>5)</sup>. This potential produces an infinite discrete hadron spectrum. The implementation of this confining force with OGE and/or Goldstone boson exchanges derived from chiral symmetry breaking, or other effective interactions, turns out to be fruitful in the construction of quark potential models providing a precise description of baryon spectroscopy. However an outstanding problem remains unsolved: all models predict a proliferation of baryon states at excitation energies above 1 GeV which are not experimentally observed as resonances. This difference between the quark model prediction and the data about the number of physical resonances is known as the missing resonance problem.

Unquenched lattice QCD points out a string breaking in the static potential between two quarks<sup>5)</sup> what should be properly incorporated in the

phenomenological description of the high energy hadronic spectrum. The spontaneous creation of a quark-antiquark pair at the breaking point may give rise to a breakup of the color flux tube between two quarks in such a way that the quark-quark potential does not rise with the interquark distance but it reaches a maximum saturation value. The simplest quark-quark screened potential, containing confinement and one-gluon exchange terms, reads:

$$V(r_{ij}) = \frac{1}{2} \left[ \bar{\sigma} r_{ij} - \frac{\bar{\kappa}}{r_{ij}} + \frac{\hbar^2 \bar{\kappa}_\sigma}{m_i m_j c^2} \frac{e^{-r_{ij}/\bar{r}_0}}{\bar{r}_0^2 r_{ij}} (\vec{\sigma}_i \cdot \vec{\sigma}_j) \right] \left( \frac{1 - e^{-\mu r_{ij}}}{\mu r_{ij}} \right) + \frac{\bar{M}_0}{3} \quad (1)$$

where  $r_{ij}$  is the interquark distance,  $m_{i,j}$  the masses of the constituent quarks,  $\vec{\sigma}_{i,j}$  the spin Pauli operators, and  $\bar{M}_0$  is a constant. The screening multiplicative factor appears between parenthesis on the right hand side.  $\mu$ , the screening parameter, is the inverse of the saturation distance and its effective value is fitted together with the other parameters,  $\bar{\sigma}$ ,  $\bar{\kappa}$ , and  $\bar{\kappa}_\sigma$ , to the spectrum.

For nonstrange baryons the model predicts quite approximately the number and ordering of the experimental states up to a mass of 2.3 GeV <sup>6, 7)</sup>.

More recent lattice calculations <sup>5)</sup> show that the  $Q\bar{Q}$  potential saturates sharply for a breaking distance of the order of 1.25 fm corresponding to a saturation energy of about twice the  $B$  meson ( $Q\bar{q}$ ) mass, indicating that the formation of two heavy-light subsystems is energetically favored. A saturated quark-quark potential incorporating this effect can be parametrized as:

$$V(r_{ij}) = \begin{cases} V_{sr}(r_{ij}) & r_{ij} < r_{sat} \\ \sigma r_{sat} & r_{ij} \geq r_{sat} \end{cases}, \quad (2)$$

where

$$V_{sr}(r_{ij}) = \frac{1}{2} \left[ \sigma r_{ij} - \frac{\kappa}{r_{ij}} + \frac{\hbar^2 \kappa_\sigma}{m_i m_j c^2} \frac{e^{-r_{ij}/r_0}}{r_0^2 r_{ij}} (\vec{\sigma}_i \cdot \vec{\sigma}_j) \right] + \frac{M_0}{3} \quad (3)$$

whose parameters are given in Ref. <sup>8)</sup>. The calculation of the spectrum proceeds exactly in the same manner as in Ref. <sup>6)</sup>, to which we refer for technical details. It is worth to remark that the presence, in the three-body problem, of two-body thresholds (for only one quark to be released), apart from the absolute three-body ones (saturation energy), may represent further constraints in the applicability limit of the model to any particular channel. The results obtained are represented in Fig. 1. As in Ref. <sup>6)</sup> we have also included the predicted states close above the thresholds.

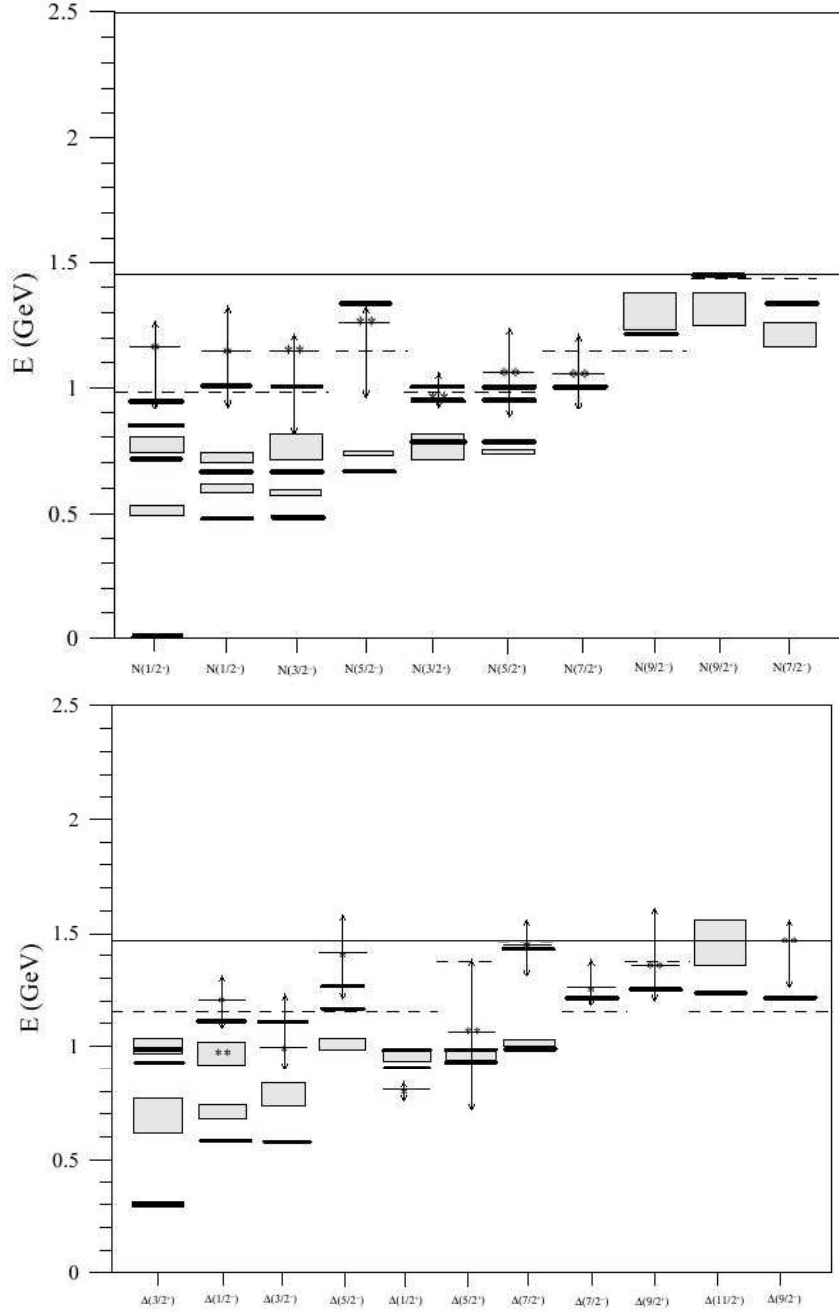


Figure 1: Relative energy nucleon (upper part) and  $\Delta$  (lower part) spectra for the screened potential of Eq. (2) with the parameters of Ref. 6). The thick solid lines represent our results. The shaded region, whose size stands for the experimental uncertainty, represents the experimental data for those states cataloged as (\*\*\*) or (\*\*\*\*) states in the Particle Data Book. Experimental data cataloged as (\*) or (\*\*) states are shown by short thin solid lines with stars over them and by vertical lines with arrows standing for the experimental uncertainties. Finally, we show by a dashed line the  $1q$  ionization threshold and by a long thin solid line the total threshold.

The quality of the description of the light baryon spectra is remarkable since apart from keeping the same level of quality than in the low and medium-lying spectrum a perfect one to one correspondence between our predicted states and the experimental resonances for any  $J^P$  is obtained. Similar results are obtained using the screened potential given in Eq.1. The number and ordering of states remains unaltered. The sharp potential tends quite generally to push upward the highest energy states. In other words the screened potential is quite similar to the closest physical approach to a nonscreened potential, represented by the sharp interaction, that takes effectively into account the effect of the baryon decay to open channels in order to select the observed resonances.

### 3 The heavy sector

Since the discovery at BNL <sup>9)</sup> and posterior confirmation at Fermilab <sup>10)</sup> of the existence of charmed baryons in the late 70's, an increasing interest on heavy baryon spectroscopy arose. It became evident that baryons containing heavy flavors  $c$  or  $b$  could play an important role in our understanding of QCD. Since then, several new hadrons containing a single charm or bottom quark have been identified <sup>11)</sup>. While the mass of these particles is usually measured as part of the discovery process, other quantum numbers such as the spin or parity have often proved to be more elusive. For heavy baryons, no spin or parity quantum numbers of a given state have been measured directly. Therefore, a powerful guideline for assigning quantum numbers to new states or even to indicate new states to look for is required by experiment.

Several criteria can be chosen to fit the confinement strength in the baryon spectra, being the most usual ones to fit the energy splitting between the nucleon and its first radial excitation (roper resonance) or to fit the splitting with its lowest orbital excitation (negative parity). We show the differences using both criteria in Fig. 2. On the left hand side we show the spectra obtained in the first case, named [A], and on the right hand side the results obtained for the later, named [B]. A better agreement is observed with the model reproducing the orbital excitations of the light baryon sector <sup>12)</sup>. There is no experimental state that we do not predict and there is no low-lying theoretical resonance that has not been observed. The recently discovered  $\Sigma_c(2800)$  <sup>13)</sup> would correspond to an orbital excitation with  $J^P = 1/2^-$  or  $3/2^-$ , any other correspondence

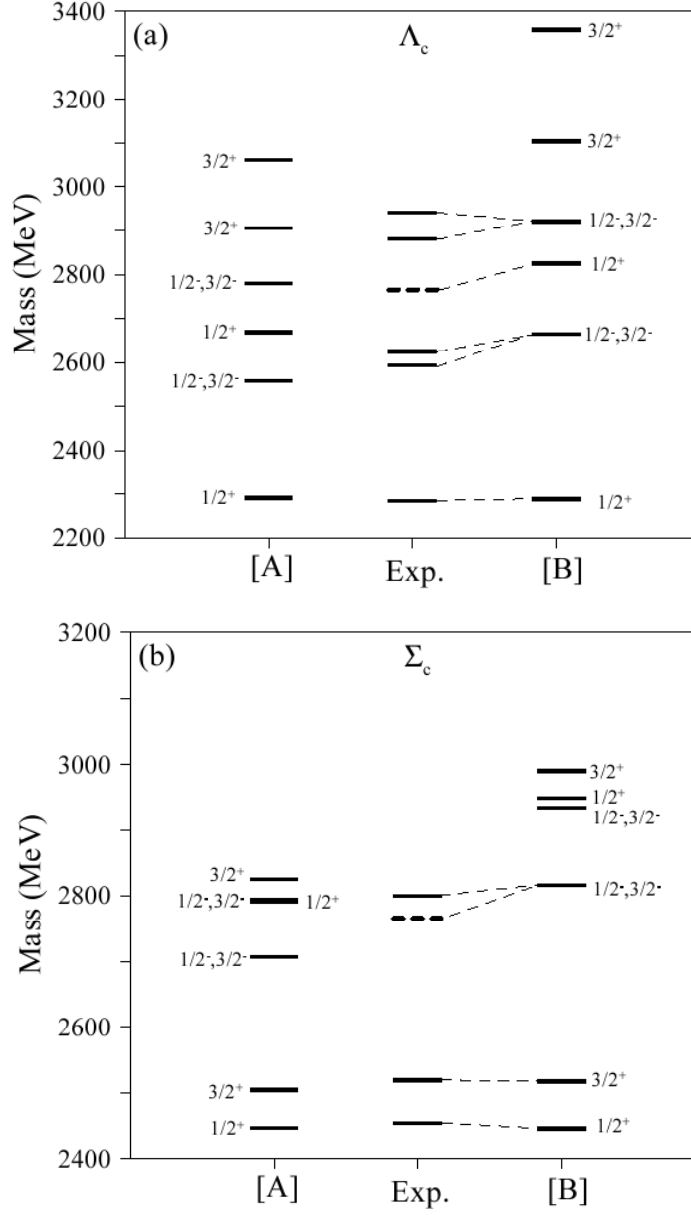


Figure 2: (a) Spectra of  $\Lambda_c$  for two different confinement strengths compared to experiment. (b) Same as (a) for  $\Sigma_c$  states.

being definitively excluded. For  $\Lambda_c$  baryons, the recently confirmed as a  $\Lambda_c$  state,  $\Lambda_c(2880)$ <sup>14)</sup>, and the new state  $\Lambda_c(2940)$ <sup>14)</sup> may constitute the second orbital excitation of the  $\Lambda_c$  baryon. Finally, there is an state with a mass of 2765 MeV reported in Ref.<sup>15)</sup> as a possible  $\Lambda_c$  or  $\Sigma_c$  state and also observed in Ref.<sup>13)</sup>. While the first reference (and also the PDG) are not able to decide between a  $\Lambda_c$  or a  $\Sigma_c$  state, the second one prefers a  $\Lambda_c$  assignment. As seen in Fig. 2, this state may constitute the second member of the first orbital excitation of  $\Sigma_c$  states or the first radial excitation of  $\Lambda_c$  baryons. An experimental effort to confirm the existence of this state and its decay modes would help on the symbiotic process between experiment and theory to disentangle the details of the structure of heavy baryons.

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